On the Effects of a Vortex Breaker on the Wake Meandering Characteristics of a Miniature Wind Turbine

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ABSTRACT

This investigation sought to understand how the addition of a vortex breaker to the nacelle of a miniature wind turbine might disrupt, enhance, mitigate, or otherwise alter the meandering characteristics of the wake flow. Velocity measurements were taken in the wake of the turbine in a wind tunnel experiment, and analyzed with MATLAB and Microsoft Excel. Three vortex breakers were designed, and each of these cases was compared to the wind turbine with no nacelle additions. A decrease in mean streamwise wake velocity and appreciable shifts in the peak meandering frequency and intensity were observed. Peak spanwise frequencies were normalized by the mean wake velocity to compensate for effects due to increased drag on the turbine when the vortex breakers were added. This normalization is appropriate, as previous experiments have shown that wake meandering scales with the Strouhal Number (St = fD/U) for utility and small-scale turbines [1]. Meandering frequency variations between vortex breaker cases and the bare nacelle case were partially attenuated when analyzing Strouhal percent differences. This suggests that the alterations in the meandering characteristics were a combinatorial result of both increased nacelle drag and vortex interactions between the nacelle vortex and blade tip vortices.

1. Introduction

Dr. Michele Guala and his team have been researching the wake produced by wind and marine hydrokinetic turbines. It is known that after a fluid passes through the rotor, the wake flow does not continue in a linear path, but experiences meandering oscillations. It has been postulated that this phenomenon is a result of the interaction between the hub vortex formed at the nacelle and the tip vortices shed from the blade tips [2]. This wake meandering can be seen in Figure 1.

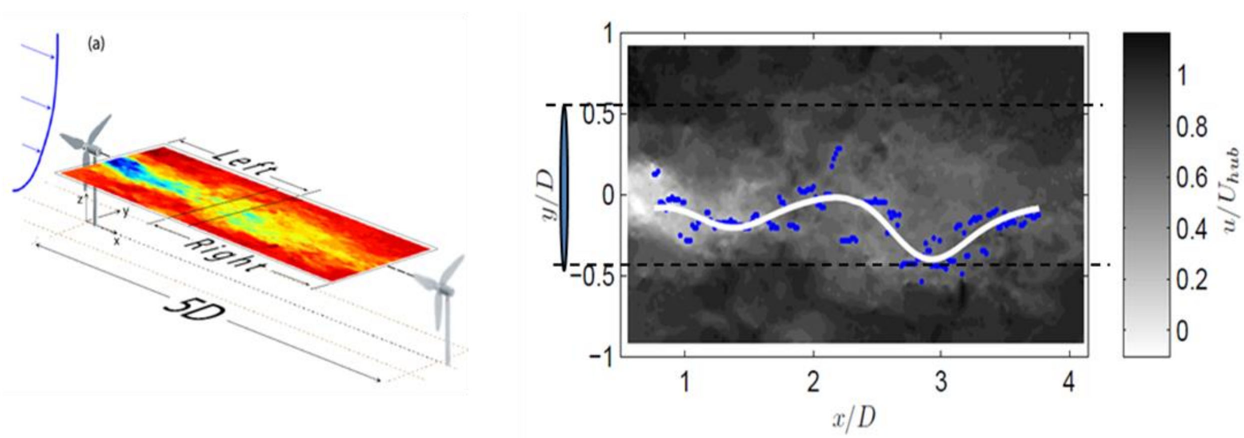

Figure 1. Particle image velocimetry (PIV) measurements of wake meandering (from Howard et al, 2015)

Preceding this investigation was a series of experiments in the wind tunnel at the Saint Anthony Falls Laboratory (SAFL). Various geometrical modifications, known as vortex breakers, were manufactured and attached onto the nacelle. In this study, the research efforts attempted to better understand how the addition of these vortex breakers affected the meandering frequency and intensity. This understanding would be beneficial for increasing the areal density of turbine placement in a grid and the total power plant energy capacity. The ultimate goal is to manipulate the wake properties in such a way to produce laminar inflow conditions for downstream turbines. This would reduce structural loads on the turbine, therefore increasing life expectancy, while also providing for more efficient wind power extraction. For now, the focus is on exploring ways in which the designed vortex breakers affect the wake flow.

2. Wind Tunnel Experiment

2.1 Vortex Breakers

Using SolidWorks and 3D printers, a combination of Lulzbots and Makerbots, provided by the Mechanical Engineering Student shop, three different variations of vortex breakers were designed and manufactured. These vortex breakers were designed for a miniature wind turbine provided by Dr. Guala. The four variations are shown in Figure 2.

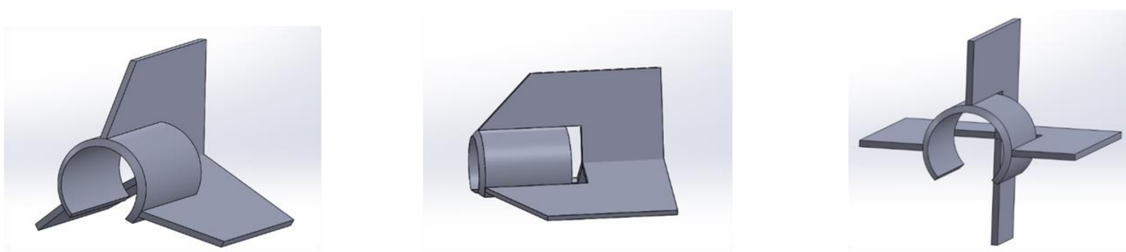

Figure 2.

(a) Three Short Fins
Fin Height (above Nacelle) = 1.0 cm
Fin Depth = 1.0 cm
Thickness = 1.0 mm

(b) Three Long Fins
Fin Height (above Nacelle) = 1.0 cm
Fin Depth = 1.5 cm
Thickness = 1.0 mm

(c) Four Fins
Fin Height (above Nacelle) = 1.0 cm
Fin Depth = 1.0 cm
Thickness = 1.0 mm

2.2 Experimental Set-up and Methods

The SAFL wind tunnel was set to 209 rpm to ensure the wind velocity maintained a nearly constant 5 m/s. The wind tunnel temperature was kept constant at 21.4 ± 0.2 °C for the duration of the experiment. A hot wire anemometer was used to measure the streamwise (the direction parallel to the flow) and spanwise (the direction perpendicular to the flow) velocities of the wake. The measurements of velocity were taken at hub height at distances behind the turbine proportional to the diameter of the blades (i.e. 2D, 4D, 6D, 8D, 10D where D ≈ 128 mm). At each distance, the turbine by itself (referred to as the bare nacelle case) and the turbine with each of the vortex breaker additions were tested for three minutes, for a total of twenty trials. Three tests were conducted intermittently with no turbine in front of the anemometer to record the velocity of the wind tunnel to serve as a free stream velocity baseline. The sample frequency was 20,000 Hz, and LabVIEW programs were used to collect data. A laser tachometer was pointed at the tip of the blades to record the angular velocity. This was to observe any fluctuations in the speed of the blades when the vortex breakers were added, because the drag and power coefficients of a wind turbine are related to the angular velocity by way of the tip speed ratio (λ =

blade tip speed/incoming wind speed). Figure 3 shows this relationship between tip speed ratio and drag and power coefficients for a different model wind turbine [1]. If the angular velocity were to vary significantly, the drag on the turbine would result in different wake characteristics. To mitigate this effect, a voltage was applied to the turbine generator to provide an adjustable counter torque to maintain a constant tip speed ratio of ~3.4 throughout the experiments.

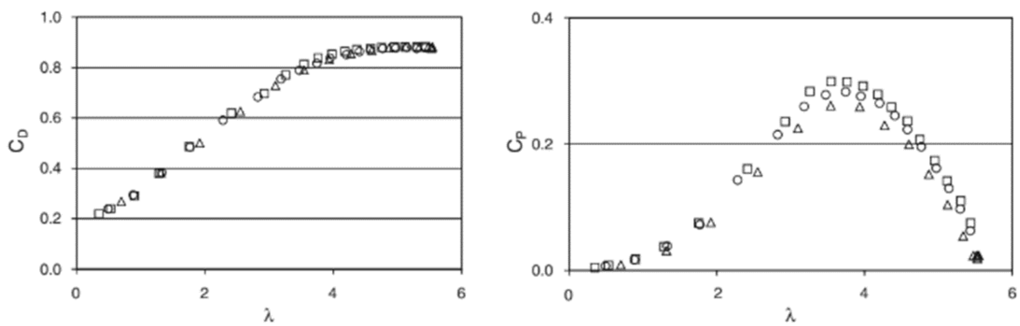

Figure 3. *Drag and power coefficients as a function of the tip speed ratio λ: ○, $U_\infty = 8{\cdot}3\ m\ s^{-1}$, no turbulence; □, $U_\infty = 8{\cdot}5\ m\ s^{-1}$, 4·5% grid turbulence; △, $U_\infty = 5{\cdot}5\ m\ s^{-1}$, no turbulence*

3. RESULTS: Velocity Deficit

Figure 4 shows the streamwise mean velocity profiles for each nacelle configuration. From the velocity profile, the velocity deficit can be observed. This demonstrates how the velocity is affected over distance behind the turbine. Note that only distances 4D – 10D are included in this plot. For the rest of this investigation, except for when calculating cumulative average velocities (see section 4.2), results from 2D are ignored for three primary reasons. First, fluid motion this close to the turbine rotor is too

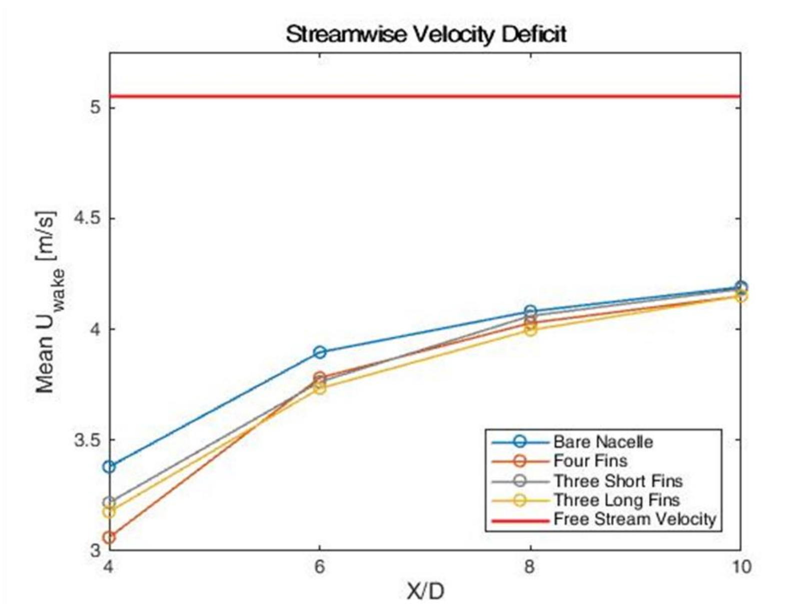

Figure 4. *Streamwise mean velocity profiles for each nacelle configuration. Notice that the velocity deficit of the nacelle cases with respect to the bare nacelle decreases with downstream distance. All of the profiles tend toward the freestream velocity at further distances from the turbine.*

chaotic to stabilize. Second, the purpose of this investigation is to eventually apply the wake manipulation to a utility scale wind turbine. Placing a second turbine 2D downstream from the first would result in inefficient power extraction and unnecessary structural loading. Third, previous studies have shown that wake meandering onset does not begin until ~4D [3]. In Figure 4, it can be seen that there is a decrease in average velocity for the three cases with vortex breakers as compared to the bare nacelle case. The cause of this can be attributed either to increased drag due to the presence of the vortex breakers, or due to interactions between the blade tip vortices and the nacelle vortex. The cause and effect of this deficit on the wake oscillation frequency will be explored throughout the following sections.

4. RESULTS: Spectral Analysis

4.1 Velocity Spectra

The incoming signal captured by the hotwire anemometer is a sinusoid of unknown frequency and amplitude that can be represented as the sum of many sinusoids each with a distinct frequency and amplitude. This process of decomposing the signal into its frequency components was done with the fast Fourier Transform algorithm. See section 4.3 for a more detailed description of this process.

For each of the twenty trials, a velocity spectra and pre-multiplied spectra was generated in both the streamwise and spanwise directions, resulting in 40 plots. The spectra were estimated using a fast Fourier Transform and a Hanning window and computed using MATLAB. Figure 5 shows the streamwise and spanwise spectra and pre-multiplied spectra for the bare nacelle and four fins case at 6D. It can be seen here that the spanwise peaks are much more distinct than that of the streamwise. For accuracy of peak identification, the spanwise spectra were used for the majority of the analysis. Ambiguity in the streamwise peaks was considered when calculating uncertainties in section 4.3.

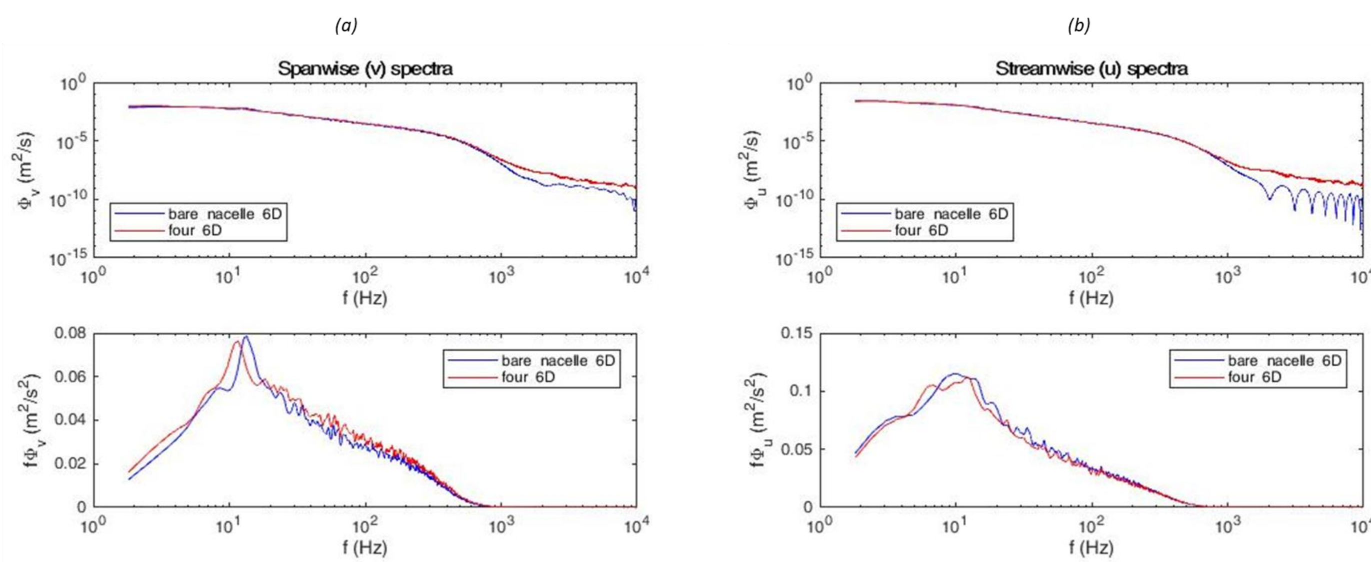

Figure 5. *In the velocity spectra (top plot of both a an b), the y-axis, Φ, is the turbulent energy at each frequency scale in the flow. Thus, each coordinate pair (data point) represents the amount of energy that is oscillating at the given frequency. Note that the pre-multiplied spectrum is used for convenient observation of the peak and does not represent the physical energy levels.*

The velocity spectra shows how the turbulent energy is redistributed after the flow is disrupted by the wind turbine. When there is a peak in the velocity spectra plot, this tells us that the wake will predominantly meander at that frequency. The explanation for this is as follows. Since the integral of the velocity spectra gives the total energy in the wake, the peak corresponds to the frequency at which the majority of turbulent energy resides, indicating that the wake oscillates at this frequency. Therefore, the wavelength that corresponds to the peak frequency can be used to see what the wake looks like.

4.2 Peak Frequency Analysis

From the velocity spectra, all of the peak frequencies and their corresponding pre-multiplied amplitude were gathered. As mentioned above, the pre-multiplied peak does not represent physical energy levels, however the value can indicate whether there was an increase or decrease in peak energy. Analyzing the trends among the peak frequencies will reveal whether or not the vortex breakers had an observable effect on the meandering.

Any shift in the peak would indicate the wake was manipulated in some way different than it would be without any perturbations on the nacelle. For instance, imagine the peak frequency of a spectra with a vortex breaker were to shift to the right with respect to the bare nacelle spectra. This would mean when the vortex breaker is introduced, more shortwave oscillations are prevalent in the wake, and comparatively less long longwave oscillations. In other words, a shift to the right (toward higher frequency) would indicate there is more shortwave, high frequency turbulence in the wake as compared to the bare nacelle.

The percent difference between each spanwise peak frequency and the bare nacelle spanwise peak frequency was calculated and plotted in Figure 6. Here it can be seen that the peak frequencies were shifted anywhere between |4-13%|. Note that negative percentages indicate a shift toward lower frequency scales (left), and positive toward higher frequency scales (right). Error bars are discussed in detail in section 4.3.

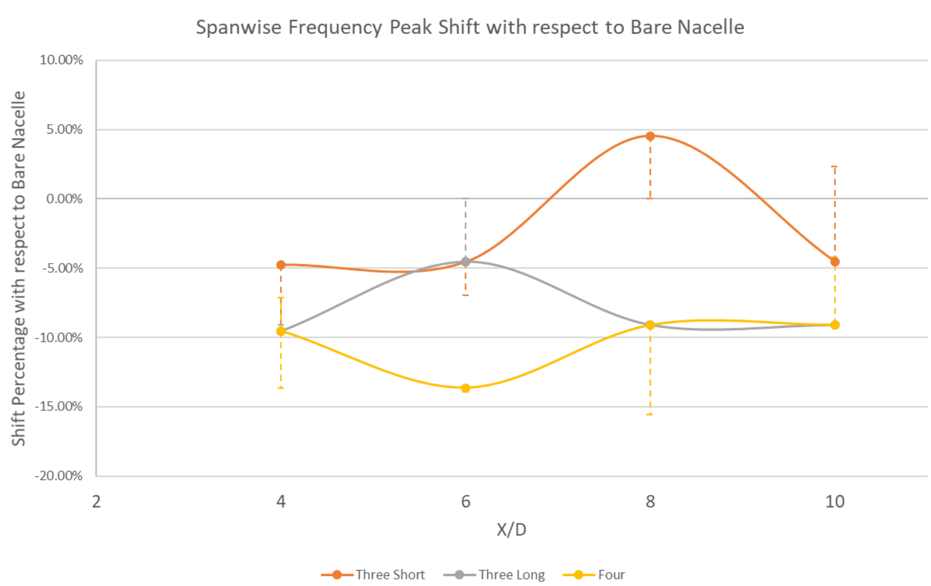

Figure 6. *The spanwise peak frequencies are represented as a percent difference with respect to the bare nacelle peak frequency. The uncertainty bars account for discrepancies in peak identification due to limitations of spectral resolution, and are discussed in section 4.3.*

Recall from the velocity deficit plots that there was a decrease in mean velocity with respect to the bare nacelle, but the cause of this deficit was uncertain. In Figure 6, it was shown that there was a noticeable shift in peak frequency when the vortex breakers were added to the turbine nacelle. It is not obvious whether or not the velocity deficit is due to drag or a frequency change. Similarly, it is not obvious whether this frequency shift is due to decreased velocity or to vortex interactions. In attempts to resolve the ambiguity in discerning whether drag or vortex interactions caused the frequency shift, the peak frequencies were normalized by the cumulative average streamwise velocity at each distance. Normalizing by velocity effectively compensates for shifting due to increased drag. If, when normalized, the frequency shift percentages shown in Figure 6 are attenuated, it can be said that the frequency shifting is due to drag.

The Strouhal Number

$$St = \frac{fD}{U} \tag{1}$$

, where D is the rotor diameter, is a common dimensionless frequency parameter used in wake meandering experiments. It has been shown in previous studies that meandering frequency for small and utility scale turbines scales with the Strouhal Number [1]. Since, for each case in this investigation, the peak shift with respect to the bare nacelle case is of interest, the Strouhal ratio is defined:

$$St' = \left(\frac{f_{peak_{Vortex\ Breaker}} D}{U_{C_{Vortex\ Breaker}}} - \frac{f_{peak_{Bare\ Nacelle}} D}{U_{C_{Bare\ Nacelle}}} \right) \Bigg/ \frac{f_{peak_{Bare\ Nacelle}} D}{U_{C_{Bare\ Nacelle}}} \tag{2}$$

It can be seen here that rotor diameter, D, cancels and therefore is not used in the following normalizations. U_C is the cumulative average streamwise velocity. U_C was calculated as follows for the distance of 4D:

$$U_C = mean\left(U_{average_{2D}} + U_{average_{4D}}\right) \tag{3}$$

Where $U_{average}$ is distinct for each nacelle configuration. To obtain U_C for 6D, the same equation above would be used, with $U_{average_{6D}}$ included in the mean. The same was done for 8D and 10D. Figure 7 shows the St’ shift by percentage with respect to the bare nacelle for each of the vortex breakers. The peak frequency shifts by percent shown in Figure 6 are overlain for convenience of comparison. The effect of wake velocity normalization (i.e. drag compensation) can be seen by mentally translating the solid line curve (frequency shifts) to the dashed line (St’ shifts). When the dashed line is nearly zero, this represents when the observed shift in frequency was attenuated when drag was compensated for.

Figure 7. (a)

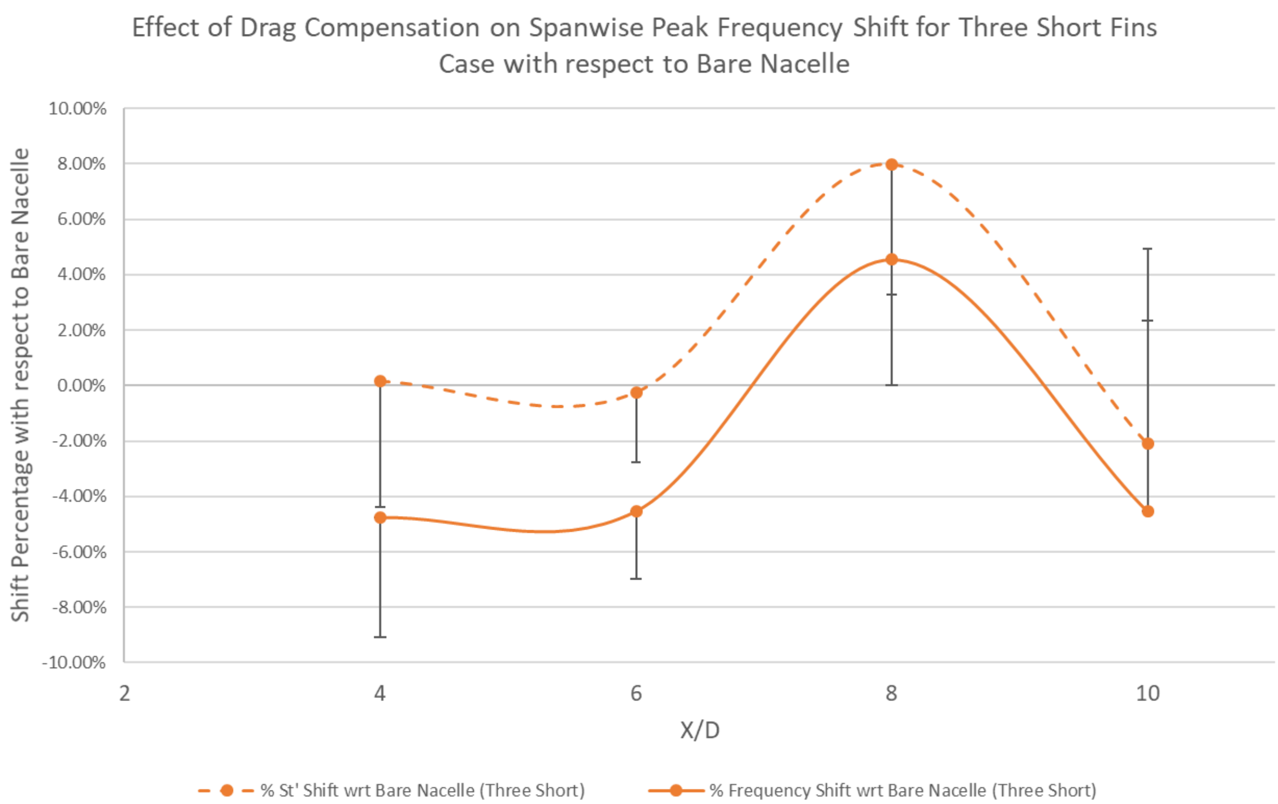

Figure 7. (b)

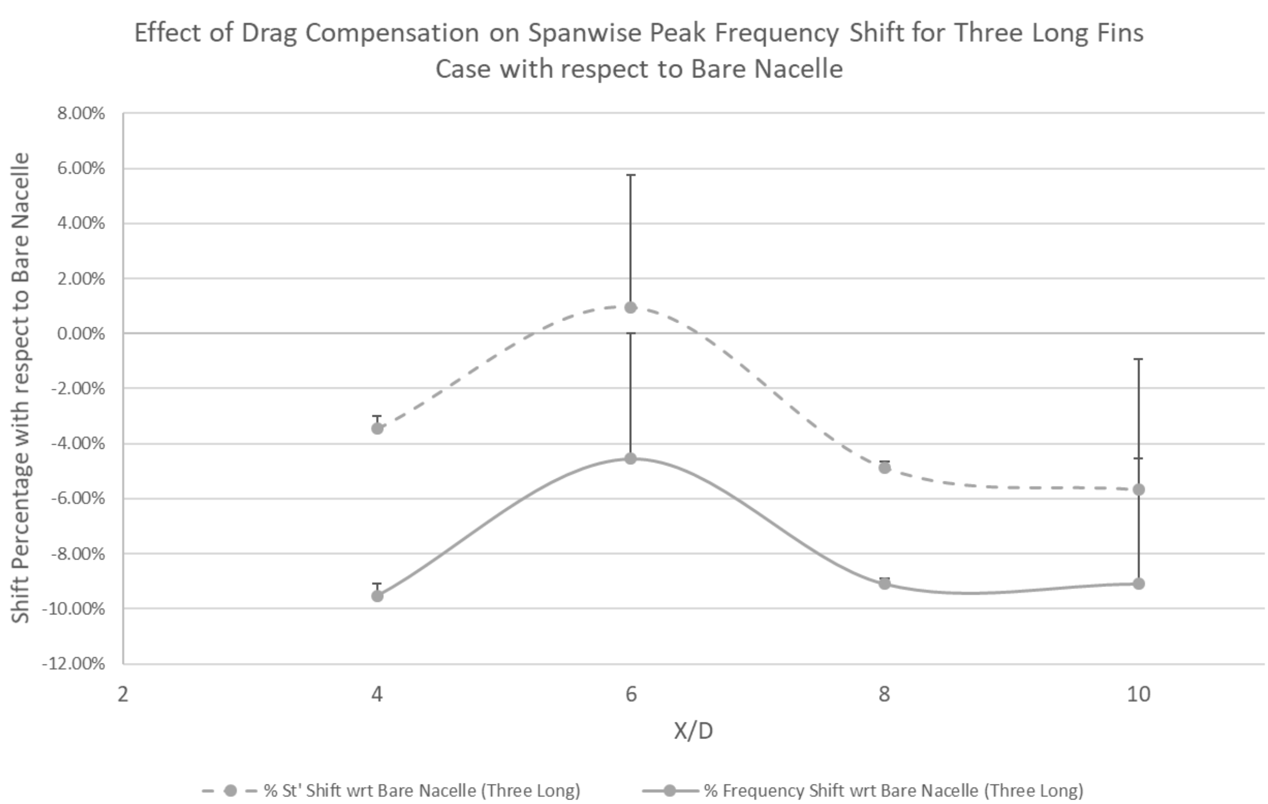

Figure 7. (c)

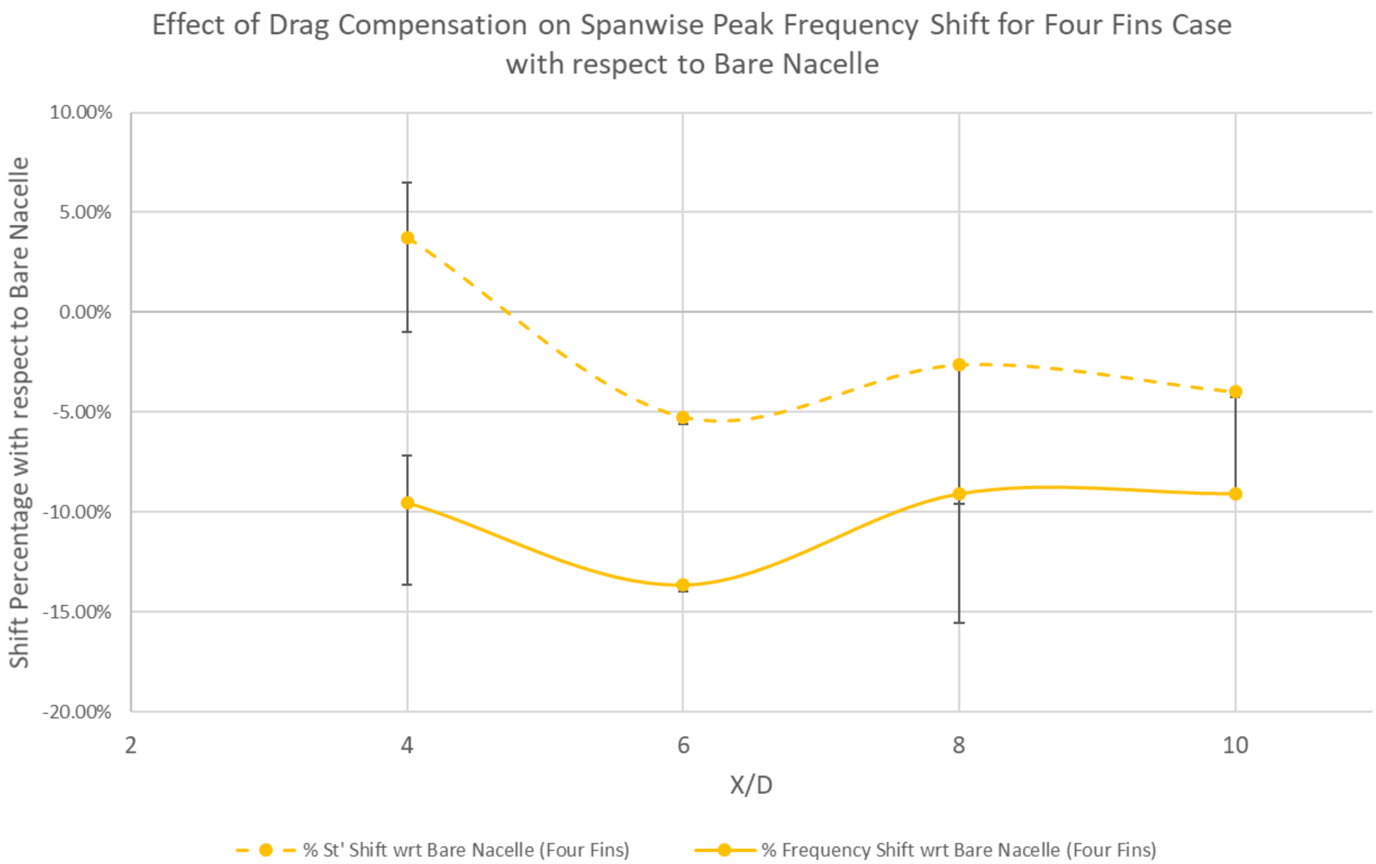

Figure 7 shows the spanwise peak Strouhal ratios represented as percent differences. Recall that by definition, the Strouhal ratio shown in Equation (2) indicates shift with respect to the bare nacelle case. The peak frequencies by percent difference from Figure 6 are shown here as well (sold lines) for convenient comparison.

4.3 Uncertainty

The uncertainty in peak frequency can be largely attributed to limitations in the spectral resolution. To compensate for this, various Hanning Window lengths were applied to the velocity signal obtained by the hotwire anemometer. To understand this fully, let us review the basics of the signal processing used here.

In experiments, it is impossible to take an infinite sample of a signal. At some point, the data collection must start and stop. Therefore, instead of an infinitely repeating function, the obtained sample is a truncated section of a theoretically infinite signal. According to Fourier analysis, any signal can be decomposed into a number of discrete frequencies, or a spectrum of frequencies over a given range [4]. The Power Spectral Density of a series of data points describes the distribution of power into the frequency components composing that signal. Using the Fast Fourier Transform (FFT) algorithm, the power spectrum can be generated. This is what is shown in Figure 6. One assumption of the FFT is that the sample taken repeats indefinitely. This assumption results in discontinuities at the boundaries of the signal. These sharp transitions result in frequency peaks in the spectrum that are not actually part of the signal. Therefore, the spectrum contains excess energy from these artificial peaks, and this energy is spread out amongst the other frequencies. This is called spectral leakage, and results in a false spectrum.

To reduce spectral leakage, a window can be applied to the sample. A window is a function that the signal can be multiplied by in order to collapse the amplitudes at the discontinuities. The window function is, essentially, equal to one everywhere, but slopes to zero at its edges, thus eliminating the frequency contributions from the sharp transitions. The window size is defined by the number of data points it is applied to. Changing the window size alters the resolution of the spectra by defining the allowable frequency values. If the window is too large, the peak cannot be identified because there will be an overwhelming amount of noise in the signal. A window that is too small effectively smooths the signal too much, resulting in a dampened and erroneous peak.

A primary window size of 15,000 points was used for the investigation. However, it was noticed that for different cases and different distances, a window of 10,000 or 20,000 could resolve a better-defined peak, particularly in the streamwise direction. Since there was no obvious “one size fits all”, all of the calculations were computed for all three window sizes for each case. The different windows resulted in slightly different peak frequencies, thus the error bars indicate the potential range over which the true peak frequency might reside.

5. Discussion: An Interpretation of the Spectra Peak Shifting

It is clear from Figure 7 that not all peak shifts were fully attenuated when drag effects were compensated for, yet a few appeared to be. This is perhaps an indication that frequency shifting can be mostly attributed to vortex interactions, but also due to increased drag on the nacelle. However, the frequency shifting is not overwhelmingly consistent at all distances for all vortex breakers. Take 6D, for example. In the case of three short and three long fins, the peak shifting is almost fully attenuated when drag is compensated for, but this is not the case for the four finned vortex breaker. The reverse is true at 8D. But, when considering the size of uncertainty, it is possible that the true frequency shift does not collapse when normalized.

It is also seen that the direction of frequency shifting is not consistent across distances or cases. For example, consider the transition from 6-8D for the three short and three long finned vortex breakers. Three short goes from a positive shift to a negative shift, and three long does the opposite. Meaning, as the wake traverses over distance, the three short fins meandering transitions from being comprised of mostly shortwave oscillations to having mostly longwave oscillations with respect to the bare nacelle, and vice versa for the three long finned vortex breaker. These attenuation inconsistencies across distances and vortex breakers might imply that more complicated large scale wake characteristics could be influential in defining the meandering.

It is not clear as to how or why the peak wake frequency is changing, however the purpose of this investigation was to see whether or not an alteration to the wake meandering would be observed. It makes sense that adding a vortex breaker would affect the wake meandering for two reasons – increased drag and vortex interactions.

Drag

A wind turbine sheds structures like a bluff body, similar to that of the Von Karman vortex street [1]. Figure 8 shows the streamlines for flow over a cylinder, a bluff body. It can be seen here that when comparing the wake of a laminar boundary layer (case 4 in Figure 8) to the wake of a turbulent boundary layer (case 5), the wake is stabilized in the turbulent case. A turbulent boundary layer can be induced by increasing surface roughness or adding fins, and this can reduce structural oscillations [5]. Adding a vortex breaker is like adding roughness to a cylinder, thus, we expect a more stable wake. However, as far as how this 'stabilized' wake specifically influences oscillations, it does not say.

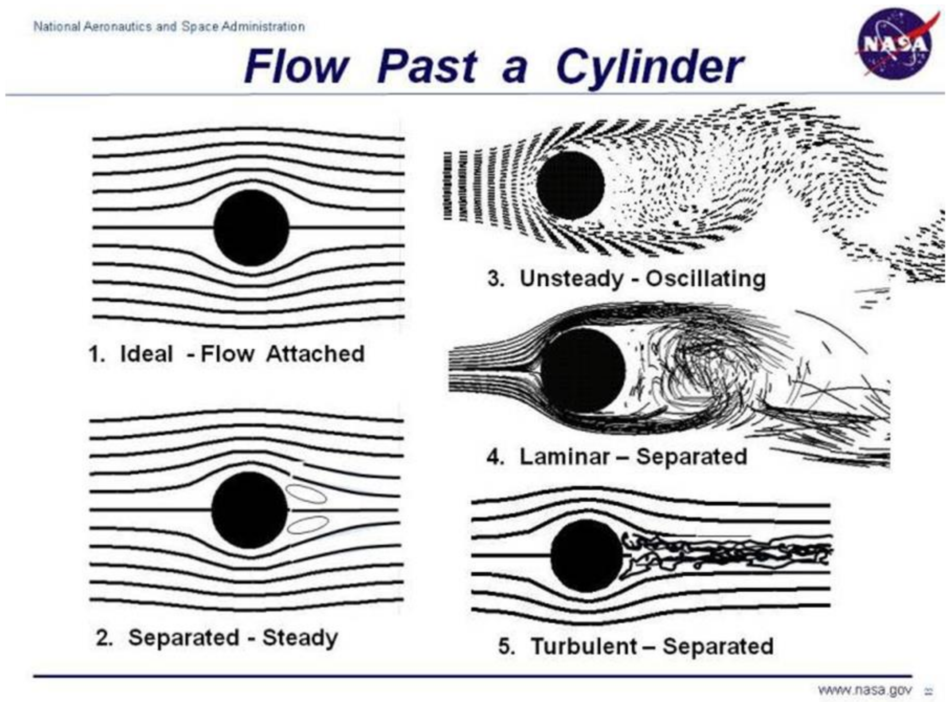

Figure 8. Shows the streamlines for two dimensional flow past a cylinder for five different cases. [6]

A more stable flow (i.e. streamlines are more attached across the body) could result in less turbulent kinetic energy (TKE) in the wake. This is confirmed in Figure 9 where the peak pre-multiplied amplitudes are plotted at each downstream distance. There is a general decreasing trend toward lower amplitude with respect to the bare nacelle case. While these peak amplitudes do not represent the energy scales physically, they can serve as a representative turbulent energy and do indicate that there is a change in peak energy, particularly at the near to mid-wake ranges. In determining the representative turbulent energy, the 20,000 Hanning Window size was used. This is because as window size decreases, the longwave scales are discarded by the algorithm, thus reducing the overall area under the curve (i.e. total energy) and directly reducing the peak amplitude. Therefore, the higher window results in the most accurate peak intensity.

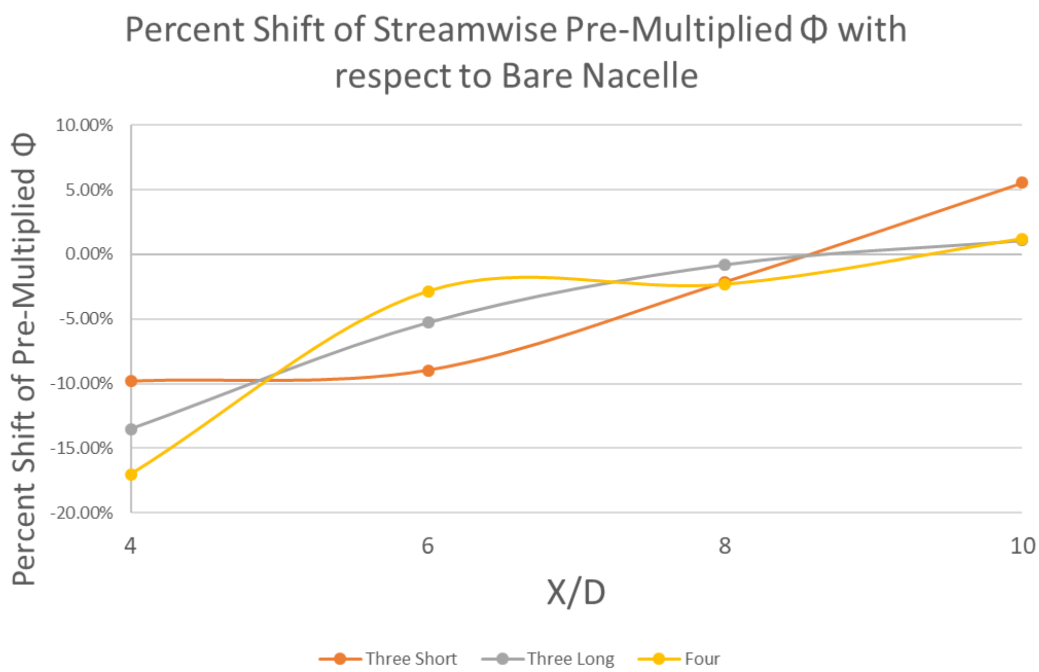

Figure 9. The wake intensity (i.e. amount of turbulent kinetic energy in the wake) can be represented by the pre-multiplied amplitude, but does not directly relate to the physical energy in the flow. Here, the intensity of each vortex breaker case is plotted as a percent difference with respect to the bare nacelle case.

Vortex Interactions

In theory, the presence of a vortex breaker around the nacelle would, not surprisingly, reduce or "break" the nacelle vortex. Since meandering has been shown to be a result of interplay between blade tip vortices and the nacelle vortex, reducing one of these components should affect the oscillatory behavior [2]. When the nacelle vortex and the blade tip vortices collide at the annular shear layer, chaotic mixing occurs and results in increased mean velocity and TKE. By reducing the nacelle vortex, mixing is reduced. Therefore, the reduced wake energy shown in Figure 9 could be due to increased drag or these vortex interactions.

6. Conclusion

Recall that the goal of this research project, as an integral piece of a larger investigation of wind turbine wake meandering, was to delve into the analysis of peak frequency oscillation shifting as a result of adding vortex breakers onto the nacelle of a wind turbine. As shown in Figure 4, there was a slight velocity deficit in the mean wake flow in the presence of the vortex breakers. This reduction could be due to drag or vortex interactions. First, it is possible that the presence of the vortex breakers effectively increased the roughness of the bluff body-like obstacle, thus reducing the turbulent kinetic energy in the wake, resulting in a velocity deficit. This slowed mean velocity and more stable wake caused by increased roughness could have induced the frequency shifting. Alternatively, the vortex breaker could have reduced the nacelle vortex, therefore reducing the interactions between the nacelle vortex and the blade tip vortices. This results in less mixing in the wake, thus reducing the mean velocity and shifting the wake frequency and intensity. To discern whether the peak frequency shift observed from the velocity spectra was due to increased drag or vortex interactions, frequency shifts were normalized by the mean velocity to compensate for drag effects. Uncertainty in identifying the peak frequency was due to varying spectral resolution, however these wide discrepancies only further show that the shifting is significant, but not quantifiable. Since the frequency shifting was partially attenuated when normalized, it is hypothesized that both drag and vortex interactions were at play in altering the meandering characteristics.

Future work

This study looked to see whether or not there was a frequency shift due to the introduction of a vortex breaker on the nacelle. It did not investigate further into reasoning why the shifting varied across downstream distance, and why some shifts were attenuated at certain distances and not others, nor did it assess whether or not this shift is desirable. It could be that shifts toward longwave oscillations would be more desirable, because if a wake is created that has predominantly high frequency energy, it will rattle the downstream turbine until failure, whereas lower frequency eddies could pass through the turbine without imparting as much structural loading. To further understand which type of frequency shifting is desired, vortex breakers with a nonzero side slip angle could be tested to attempt to induce rapid mixing in the wake. Additionally, to continue this investigation, a similar experiment could be conducted with an array of miniature wind turbines to see how the power output is affected by the inclusion of vortex breakers on upstream turbines.

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